III.A.2 Optimum Utilization of Available Space in a Vehicle through Conformable Hydrogen Vessels

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Objectives

- Select optimum designs for continuous fiber pressure vessels
- Select optimum designs for replicant conformable pressure vessels
- Design, build and test conformable pressure vessels

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- B. Weight and Volume
- C. Efficiency
- D. Durability
- E. Refueling Time
- G. Life Cycle and Efficiency Analyses
- H. Sufficient Fuel Storage for Acceptable Vehicle Range
- I. Materials
- J. Lack of Tank Performance Data
- L. Hydrogen Boil-Off

Approach

- Conduct finite element analysis of continuous fiber and replicant conformable pressure vessels
- Analyze three configurations of continuous fiber pressure vessel
- Analyze existing lattices that can be used for replicant conformable pressure vessels
- Build demonstration model of selected lattices

Accomplishments

- Proposed three possible designs for continuous fiber conformable pressure vessels. These included pressure vessels of sandwich construction, ribbed pressure vessels and pressure vessels of bucking construction.

- Demonstrated through finite element analysis that the sandwich pressure vessels are not an acceptable design due to high bending moments. This narrowed our field of research to only two designs: the ribbed design and the bucking design.
- Obtained the optimum lattice for replicant conformable pressure vessels. This lattice was obtained by evaluating the 125 lattices existing in crystallography. The optimum lattice offers multiple advantages, including high resistance to impact and high volumetric efficiency (over 80%, without considering the outer skin).
- Discovered a promising procedure for bonding struts and skin in replicant pressure vessels. This procedure uses catalyzed plastics in which the surface elements can polymerize into neighboring elements, creating a very strong bond that may meet the requirements of conformable pressure vessels.

Future Directions

- Analysis
  – Continue conceptual analyses and begin detailed analyses.
  – Model replicant skin component.
  – Conduct statistical performance modeling.
  – Utilize applied mathematics (modified group theory) of lattices.
- Conceptual design
  – Select most promising geometry for continuous fiber vessels.
  – Define engineering requirements for macrolattice components.
- Component testing
  – Begin design of component tests for continuous fiber vessels.
  – Conduct statistical testing to failure of replicant struts and connectors.

Introduction

One of the fundamental hurdles limiting the broad applicability of hydrogen vehicles is storing enough hydrogen on-board for a reasonable driving range (300-400 miles). Current technologies do not adequately address this problem. Conformable tanks offer a good solution to the problem of vehicular hydrogen storage. While the density of hydrogen is limited by fundamental physics, conformable tanks can be designed to optimally occupy available space in the vehicle, minimizing intrusion into the cargo space and improving the practicality of hydrogen vehicles. Operating pressure for hydrogen storage tanks can be relatively low (100 psi for liquid hydrogen) or very high (up to 10,000 psi for compressed hydrogen). Regular shapes (cylindrical or spherical) are the easiest for pressure vessel fabrication. However, available spaces inside a vehicle are typically not cylindrical or spherical. As a result, hydrogen tanks are typically stored in the trunk, occupying precious cargo space. A better utilization of available space in the vehicle is the key to achieving the hydrogen storage targets and improving the packaging characteristics without reducing the practicality of the vehicle. Current estimates for the improvement in hydrogen storage capacity achievable with conformable tanks range between 20% and 40% depending on the design and the geometry of the available space. Substantial research on conformability is needed to improve the characteristics of H_2 pressure vessels, both for cryogenic and ambient temperature applications. The target for this project is to meet the 2010 DOE hydrogen storage targets for cost, volumetric and gravimetric energy density: \$4/kWh, 1.5 kWh/L and 2 kWh/kg. These DOE target values are based on the entire storage system, not just the storage medium.

Approach

Two parallel paths are being pursued to achieve optimum utilization of available space in a vehicle through conformable hydrogen pressure vessels.

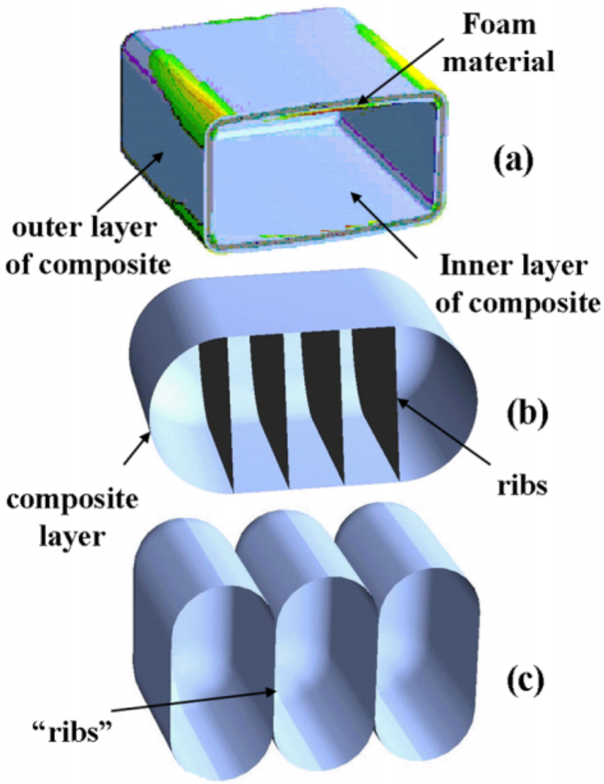

Figure 1. Three Proposed Designs for Continuous Fiber Pressure Vessels: (a) Sandwich Design, (b) Ribbed Design and (c) Bucking Design

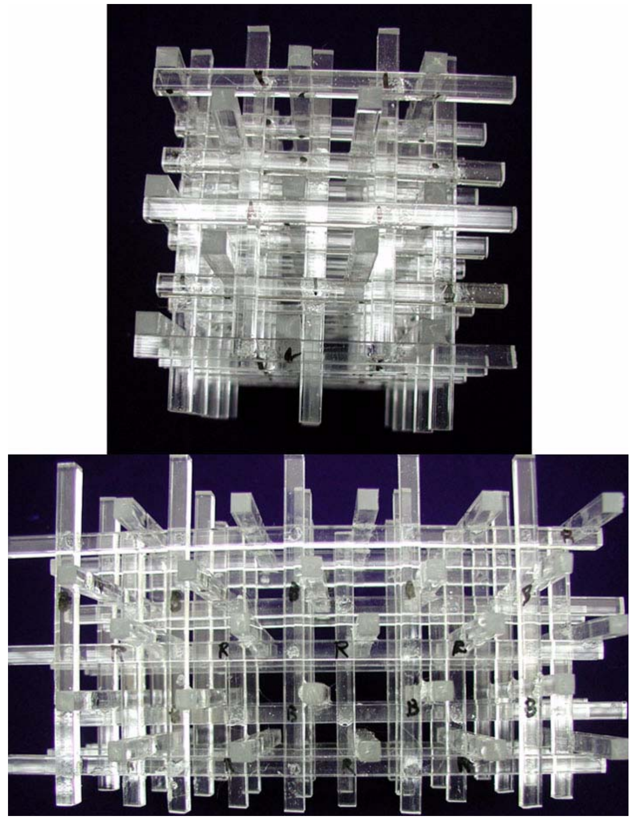

Figure 2. Two Views of the Octahedral Lattice Identified as Optimum for Replicant Conformable Pressure Vessels

The first path focuses on continuous fiber (filament winding) techniques. We have identified three potential designs for continuous fiber pressure vessels: vessels of sandwich construction, ribbed vessels and vessels of bucking design (see Figure 1). These designs have the purpose of reducing the bending moments that typically characterize conformable pressure vessels.

The second path achieves conformability through the use of “replicants,” or small components or lattices that can be glued to make free-form vessels. This second approach presents the challenge of requiring strong bonding between the structural components and the outer skin.

Results

The sandwich design for a continuous fiber pressure vessel was conceived as consisting of two layers of composites separated by a foam material that can transmit shear stresses between the inner layer and the outer layer (see Figure 1), thereby controlling bending stresses to a manageable level. However, our finite element analysis revealed that the sandwich design was not appropriate for making viable conformable pressure vessels. The reason is that the fiber can transmit shear stresses but cannot support the inner layer of composite as it tries to balloon due to internal pressure. This results in very high bending stresses in the inner composite.

The ribbed design and the bucking design remain as viable alternatives. However, an outstanding issue remains with the ribbed design: how to attach the ribs to the composite shell. This will be addressed in the future through finite element analysis and evaluation of possible bonding and construction methodologies.

We analyzed all existing lattices available for crystallography as potential arrangements for constructing ultra-conformable pressure vessels made of replicants. After an exhaustive study, we selected an octahedral structure as the optimum due to its high resistance to impact and its high volumetric efficiency (over 80% without including the outer skin). We were able to build a model of this structure for visualization and for evaluation of manufacturability (Figure 2).

Achieving a successful design for a replicant conformable pressure vessel depends critically on being able to obtain strong bonds between the structural members and the outer skin. While we are exploring the potential of existing adhesives, we have discovered a second possibility that may provide a stronger bond than available adhesives. This procedure uses catalyzed plastics in which the surface elements can polymerize into neighboring elements. This process creates a seamless joint between structural components, possibly delivering the performance required for making viable conformable pressure vessels.

Conclusions

- We have proposed three possible designs for continuous fiber conformable pressure vessels. These include the sandwich design, ribbed design and bucking design. (See Figure 1.)
- Through finite element analysis we were able to demonstrate that the sandwich pressure vessels are not an acceptable design due to the high bending moments. This narrowed our field of research to only two designs: the ribbed design and the bucking design.
- We identified an optimum lattice for replicant conformable pressure vessels. This is an octahedral lattice that provides high resistance to impact and high volumetric efficiency.
- We have discovered a promising procedure for bonding struts and skin in replicant pressure vessels. This procedure uses catalyzed plastics in which the surface elements can polymerize into neighboring elements, creating a very strong bond that may meet the requirements of conformable pressure vessels.

FY 2004 Publications/Presentations

1. **Hydrogen Storage and Transportation**, Gene Berry, Joel Martinez-Frias, Francisco Espinoza-Loza, Salvador Aceves, invited Article submitted to the Encyclopedia of Energy, Academic Press, 2004.

2. **Hydrogen Production**, Gene Berry, invited Article submitted to the Encyclopedia of Energy, Academic Press, 2004.

3. **Development and Demonstration of Insulated Pressure Vessels for Vehicular Hydrogen Storage**, Salvador M. Aceves, Gene D. Berry, Proceedings of the 15th World Hydrogen Energy Conference, Yokohama, Japan, June 27-July 2, 2004.

Patents Issued

1. **Lightweight Cryogenic-Compatible Pressure Vessels for Vehicular Fuel Storage**, Salvador M. Aceves, Gene Berry, Andrew H. Weisberg, U.S. Patent 6,708,502 B1, March 23, 2004. World Patent WO 2004/029503 A2, April 8 2004.

2. **Storage of Hydrogen by Absorption in Fluids,** Gene Berry and Salvador Aceves, Patent pending.